Resonance radiative decays as a tool for its parity determination.

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Abstract

Radiative decays of the spin 1/2 baryonic resonances R with the decay mode $R \to KN$ in case of small energy release are considered. Pentaquark Θ^+ is an example of such resonance. It is shown that in case of positive resonance parity ($J^p = 1/2^+$) corrections to the soft photon radiation formula are large even at low photon energies $\omega \gtrsim 20$ MeV and structure terms contributions may be essential, if R size $r_0 > 1$ fm. This effect is absent in case of negative parity ($J^p = 1/2^-$). Particularly, measurements of the γ-spectrum in Θ^+ radiative decays may allow us to determine Θ^+ parity.

In the present paper we show that the parity of the spin 1/2 baryonic resonance R with the decay mode $R \to KN$ (kaon and nucleon) in case of the small energe release can be determined by study its radiative decays $R \to KN\gamma$. A widely known example of such resonance is pentaquark Θ^+. So, for definiteness we consider Θ^+ decays, nevertheless, our results are general and refer to any resonance with mentioned above properties.

An exotic baryonic resonance Θ^+ with the mass $m_\Theta = 1540$ MeV and quark content $uudd\bar{s}$ had been found two years ago [1,2]. Later, the existence of Θ^+ was confirmed in many experiments. The main decay modes of Θ^+ are $\Theta^+ \to pK^0$ and $\Theta^+ \to nK^+$. Experimentally, the upper limit on Θ^+ width was found $\Gamma > 9$ MeV [2]. From the phase analysis of KN scattering [3] and theoretical analysis of Θ^+ production mechanism in $K^+d \to p\,pK^0$ [4] and K^0Xe [5] reactions more strict limitations on Γ were found: $\Gamma \leq 1$ MeV. The parity of Θ^+ is unknown experimentally. From theoretical point of view, the positive parity is favoured, since at $P = +1$ and supposed spin $J = 1/2$, KN are produced in P-wave in Θ^+ decay, and the narrow Θ^+ width can be understand easier. Since the decays $\Theta^{++} \to pK^+$ were not found, the Θ isospin is zero.

Θ^+ baryon was predicted by Diakonov, Petrov and Polyakov [6] in Chiral Quark Soliton Model (CQSM) as a member of anti-decuplet – a rotational excitation in colour-flavour space in CQSM. In this case the Θ^+ parity is +1. However, CQSM does not explain the unusual very narrow Θ^+ width. The explanation of Θ^+ narrow width based on chiral conservation [7] (where it is supposed that Θ^+ is a compact object), is valid for any Θ^+ parity $P = \pm 1$. Other models also allow $P = -1$ for Θ^+. Therefore, the measurement of Θ^+ parity is desirable.

We consider the radiative decays of pentaquark $\Theta^+ \to p\,K^0\gamma$, $\Theta^+ \to n\,K^+\gamma$ and show that the γ-spectra in radiative decays are essentially different in cases of positive and negative pentaquark parities, what would allow us to determine Θ^+ parity, basing on radiative decay data.

Consider the emission of soft gamma's with energies $\omega \leq 50$ MeV. Since the total energy release in $\Theta^+ \to KN$ decay is 100 MeV, the main part of γ spectrum is just in this domain. The wave lengths of gamma's in this domain are larger than 4 fm, and one may expect that they are larger than Θ^+ size. So, the general formula for accompanying photon emission in decay process can be used:

$$dW_\gamma(\omega) = \frac{2\alpha}{3\pi}\frac{p^2}{E_{ch}^2}\frac{d\omega}{\omega}W_{pK^0,nK^+}. \qquad (1)$$

Here $\alpha = 1/137$, p is the N or K momentum in the Θ^+ rest system, E_{ch} is the total energy of the charged particle in the final state (i.e. proton or K^+ meson) and W_{pK^0}, W_{nK^+} are the probabilities of $\Theta^+ \to pK^0$ and $\Theta^+ \to nK^+$ decays (which are approximately equal). In (1) it was put approximately $E_{ch} \gg p$. This formula is a general relation, corresponding to the case when charged particle starts to move suddenly and for this reason emits photons. Equation (1) can be derived classically. (Originally, it was obtained by Pomeranchuk and Shmushkevich for photon emission in charge exchange $n-p$ scattering [8]. In [9] formula (1) was derived for $\pi \to \mu\nu\gamma$ decay and the general character of this equation was mentioned).

In case of θ^+ positive parity the final particles in $\Theta^+ \to NK$ decay are produced in the state with orbital momentum $L = 1$, what results in strong suppression of the decay rate. The photon has spin 1 and negative parity (in case of electric field). Photon emission

takes off this suppression, what leads to relative enhancement of γ-radiation. For this reason one may expect large corrections to (1) even at low ω. No such effect exists for negative Θ^+ parity, where only small corrections to (1) take place.

Let us calculate this effect quantitatively. The phenomenological Θ^+ decay Hamiltonian is supposed to be

$$H_{int} = f\bar{\psi}_N(i\gamma_5, 1)\psi_\Theta\varphi_K + c.c., \tag{2}$$

where $i\gamma_5$ and 1 in the brackets correspond to the positive and negative Θ^+ parities, ψ_N and φ_K are isospinors and their product is an isoscalar. From (2) we get for the widths in cases of positive and negative Θ^+ parities:

$$P = +1: \qquad \Gamma = 2f^2(E_N - m_N)\frac{p}{m_\Theta}, \qquad f^2 = 0.083\,, \tag{3}$$

$$P = -1: \qquad \Gamma = 4f^2 m_N\frac{p}{m_\Theta}\,, \qquad f^2 = 1.6\cdot 10^{-3}. \tag{4}$$

In (3), (4) E_N and m_N are the energy and mass of the nucleon. The values of the effective coupling constants f^2, corresponding to $\Gamma = 1$ MeV, are also shown.

In calculation of the radiative Θ^+ decay, besides the standard Feynman diagrams, describing the photon emission by initial and final charged particles, we account the structure dependent term, where photon is emitted during the decay process. The effective Hamiltonian of this term is assumed to be

$$H_{str} = ge\bar{\psi}_N\gamma_\mu\gamma_5\psi_\Theta\frac{\partial\varphi_K}{\partial x_\nu}F_{\mu\nu} + c.c.\,, \tag{5}$$

where $F_{\mu\nu}$ is the electromagnetic field strength, and $g = g_{pK^0}$ for $\Theta^+ \to pK^0\gamma$, $g = g_{nK^+}$ for $\Theta^+ \to nK^+\gamma$. For the quantitative estimations we consider only this simplest form of H_{str}. The differential probabilities of radiative decays $\Theta^+ \to pK^0\gamma$ and $\Theta^+ \to nK^+\gamma$ in case of positive Θ^+ parity were found to be:

$$dW_{pK^0\gamma} = \frac{2\alpha}{3\pi}\frac{p^2}{E_p^2}\frac{d\omega}{\omega}B_{pK^0}(\omega)W_{pK^0}\,, \tag{6}$$

$$B_{pK^0}(\omega) = 1 + \frac{\omega}{E_p - m_p}\left(1 - \frac{m_p}{m_\Theta}\right) + \frac{3}{2}\frac{m_p\omega^2}{p^2(E_p - m_p)}\left(1 - \frac{m_p}{m_\Theta}\right)^2 - 2\frac{g_{pK^0}}{f}\frac{m_\Theta - m_p}{E_p - m_p}m_p\,\omega^2\,, \tag{7}$$

$$dW_{nK^+\gamma} = \frac{2\alpha}{3\pi}\frac{p^2}{E_K^2}\frac{d\omega}{\omega}\,B^{(\omega)}_{nK^+}W_{nK^+}\,, \tag{8}$$

$$B_{nK^+}(\omega) = 1 + \frac{\omega}{E_n - m_n}\frac{m_K}{m_\Theta} + \frac{3}{2}\frac{m_n\omega^2}{p^2(E_n - m_n)}\frac{m_K^2}{m_\Theta^2} + 2\frac{g_{nK^+}}{f}\frac{m_\Theta - m_n}{E_n - m_n}m_K\,\omega^2\,. \tag{9}$$

In (6)-(9) p was neglected in comparison with E_p, E_k and the decrease of (N, K) phase space because of the photon emission was disregarded. Only the terms linear in g are retained. The photon emission due to magnetic moments of Θ^+ and nucleon is not

enhanced and small. Indeed, the magnetic interaction has another P-parity in comparison with the electric one, therefore, the suppression remains. In the corresponding terms in (7), (9) factor $E_N - m_N$ in the denominator is absent. For this reason we omit these terms.

Numerically, in $\Theta^+ \to KN$ decay $p = 260\,\mathrm{MeV}$, $E_p - m_p \approx E_n - m_n = 36\,\mathrm{MeV}$. At $\omega = 50$ MeV the correction terms (without the structure terms) are equal to 0.76 in B_{pK^0} and 0.60 in B_{nK^+}. Therefore, the deviation from the soft photon radiation formula (1) is noticeable in these decays.

The structure constants g may be estimated as

$$g \sim 2\,\frac{1}{m_\Theta + m_d}\,\frac{1}{m_\Theta}\,r_0\,,$$

where r_0 is the Θ^+ size and factor 2 follows from comparison with the $\bar{N}NK$ coupling constant $g^2_{\bar{N}NK} \sim 5$. If $r_0 \sim 1$ fm, the last terms in (7), (9) are of order 0.3-0.5 at $\omega = 50\,\mathrm{MeV}$. The observation of this term allows one to estimate pentaquark size.

The conclusion is, the photon spectra in radiative Θ^+ decay are essentially different from one another in cases of positive and negative Θ^+ parities. For negative Θ^+ parity the spectrum in the domain of low energy photons is well described by the soft photon emission formula (1), while for positive Θ^+ parity the deviations from (1) are noticeable. Unfortunately, the radiative decay branching ratio is low: for photons in the energy interval $\omega = 10 - 50$ MeV it is about $(0.3 - 1.0)\,10^{-3}$.

The Θ^+ radiative decays were considered in [10, 11]. In [10] the strong mixing of anti-decuplet with octet was assumed and very large branching ratio $\sim 3 \cdot 10^{-2}$ was found. However, the results are not reliable, since during the calculation the gauge invariance of electromagnetic interaction was violated. [11] has some resemblance to our paper, but photon spectrum was not analysed and the main issue of our paper – the difference of spectra in cases of positive and negative parities – was not found. Moreover, in [11] it was claimed that the radiative decay rates are equal for both Θ^+ parities. This statement arises, because the authors choose very small low limit of integration over photon energy, which could not be achieved experimentally.

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